

# A model of memory, learning and recognition

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## Abstract

We propose a simple model of recognition, short-term memory, long-term memory and learning.

## 1 Introduction

For years I have been thinking about how conscience emerges from the underlying neuron clatter (by conscience I mean awareness, *i.e.* the difference between being awake and asleep). Last night the inspiration came all at once, just as visitors were arriving. I put my thoughts aside due to the visitors, but today I hasten to write them down. The model explains a lot and in hindsight is almost “obvious” (why did I not think of it before?) I mention these details because they illustrate how the mind works.

For the sake of simplicity I will be very specific, almost telegraphic. I will mention only the essential points. The reader should not take seriously the specific details. I have no pretense that the brain works with exactly the implementation I will describe below. However I do believe that many of the ideas discussed here are in fact implemented by the brain in some equivalent way.

To make this article self-contained I list in Section 2 characteristics of the brain that are relevant to our model.[1-6] Some of these characteristics have been obtained directly from experiments or observations and some have been inferred indirectly and are therefore only educated guesses. Our model is presented in Section 3. Estimates of the number of memory neurons are obtained in Section 4. Finally, conclusions are collected in Section 5.

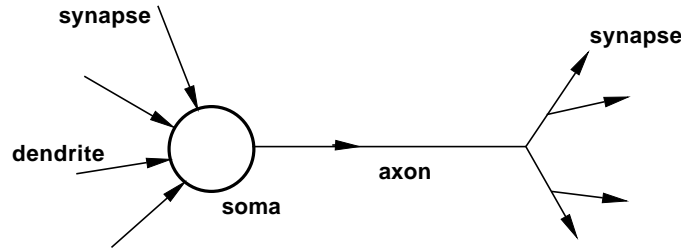


Figure 1: Schematic drawing of a neuron.

## 2 Characteristics of the brain

The human brain has approximately  $10^{10}$  “neurons”. A neuron is a cell with a central body (the “soma”) and up to  $\approx 10^5$  ramifications. One of these ramifications, called “axon”, is long and carries the output electrical pulse of the neuron. These pulses have an amplitude of 145mV and a duration of about 0.2 milliseconds. The remaining ramifications, called “dendrites”, carry the input electrical pulses to the neuron. The axon is connected to dendrites of other neurons (or to muscle cells). These connections, or “synapses”, are of a chemical nature. Each synapse carries a “weight” that can be excitatory or inhibitory. The neuron “fires”, *i.e.* sends an output impulse along its axon, if the weighted sum of inputs is above a threshold. A schematic diagram of a neuron is shown in Figure 1.

“There are roughly a quarter of a million nerve cells and two billion synapses below one square millimeter of cerebral-cortex surface.” [4]

The programing of the brain consists of the making or breaking of synapses (or more generally of the modification of the weights of the synapses). Certain programing occurs at critical periods (such as the breaking of synapses to obtain registration of the images seen by the right and left eyes[2]) and programing that occurs throughout the lifetime (such as storing information in the long-term memory).

Many brain processes occur at the same time: parallel computation is widespread.

Let us describe “sensory registers”, “short-term memory” and “long-term memory” from the point of view of a psychologist. A block diagram is shown in Figure 2. The stimuli from the environment arrive at our sense organs where they are transformed into electro-chemical impulses in neurons. This information is processed and analyzed hierarchically in the sensory registers, and in the lapse of about one quarter of a second are either discarded (if they are not interesting) or passed on to the short-term memory. This is

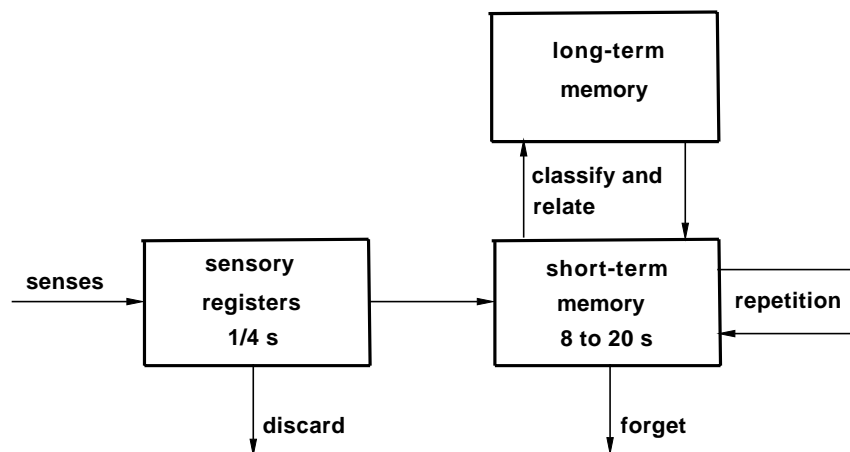


Figure 2: Memory as seen by a psychologist.

the “cocktail effect”: at a party we can pay attention to one conversation, unaware of other conversations until our name (or some gossip of interest) is mentioned.

The short-term memory can store a limited amount of information: about seven random letters, or five random words, or four random phrases, or one low resolution image. After up to eight to twenty seconds this information is discarded (forgotten) unless it is of our interest and we refresh the memory by repetition (as when we are given a new telephone number).

We can transfer information from the short-term memory to the long-term memory. This transfer requires that the information be classified and related to other information in the long-term memory. This is the learning process. As more relations are established the easier it becomes to find and recover information from the long-term memory and “re-live” it in the short-term memory. The long-term memory can store practically an unlimited amount of information which lasts for a life time (it seems that the information is lost only by disease or death).

We are aware of, or can pay attention to, a limited amount of information. Therefore we associate conscience with the short-term memory. Conscious perception takes hundreds of milliseconds.

“Neurobiologists believe that memories are encoded in the synapses, and two billion synapses per square millimeter of cortex can hold a lot of memories.” [4]

Most brain processes are unconscious. We have perception and knowledge with and without awareness.

“Long-term memory enriches our lives incredibly, but you don’t need it to be aware. All that’s necessary for base-level awareness is short-term memory



Figure 3: The filled circles represent image neurons all over the cerebral cortex that fire in response to a particular event observed by the senses. The empty circles are image neurons that do **not** fire in response to that particular event.

and attention.” [4]

“When you superimpose a PET image on an MRI image, you can see which brain structures are active in a particular task.” [4] With this technique it is discovered that different brain areas are active when, for example, we hear a word, see the word, speak the word or write the word. [4]

Let us quote Christof Koch again: “So every time I see an event, that event corresponds to electrical activity all over the brain. If I look at my friend Bill, say, his face is represented in the brain area where my face neurons are located, the hue of his face is processed in V4, the fact that he’s moving around is represented in MT, my memories of him correspond to activity in the temporal lobes, and if he talks, his speech activates my auditory cortex.” “Yet if I look at Bill I see a coherent whole.” “How come I don’t get Bill’s voice coming from the man behind him?” [4]

Different qualities (form, movement, color, depth information from binocular vision, sound, smell, ...) are processed in parallel and in hierarchical form in different parts of the brain. Presumably at the highest level of these hierarchies “all of the neurons responding to the stimulus fire at roughly the same time.” [4]

Christof Koch and Francis Crick (yes, the same Crick of the double helix) “think that if you are aware of an event, *all* the nerve cells involved in the perception of that event anywhere in the brain fire at the same time” [4] at about 40 pulses per second. They also argue that “to be aware of something you need to attend to it, and you need to put it into short-term memory”. [4]

There does not appear to be a specific place in the brain where consciousness resides. A model of distributed processing appears to best describe brain activity.

Conscience of the environment emerges in the child as he or she acquires experience. According to Piaget, before the first month of age the reflexes lack will. From one to eight months of age the child successively learns to repeat voluntarily actions that cause him pleasure, acquires the intention of his actions, searches for hidden objects, and acquires long-term goals. Self-

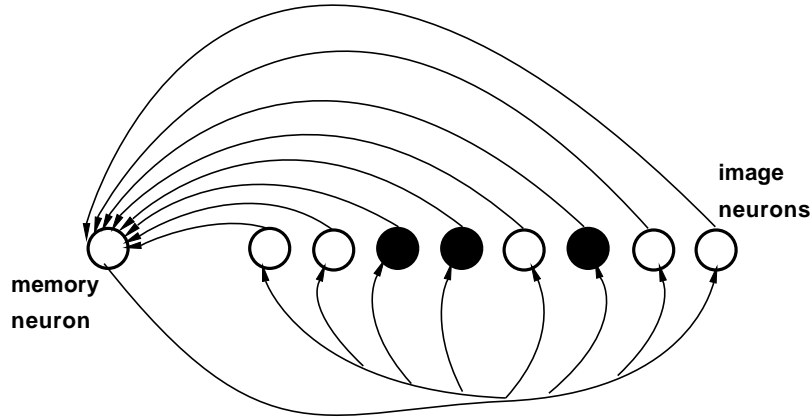


Figure 4: Image neurons, and one memory neuron before being programmed. The filled circles are image neurons that fire in response to a particular event observed by the senses.

consciousness emerges around the eighteenth month of age when the child recognizes himself in the mirror (seeing in the mirror that he has a spot painted on the nose he reaches his nose). At about the age of twenty four months the child distinguishes the words “I” and “you”. So the brain is in constant development.

### 3 A model of memory and recognition

The following is a simplified model of memory and recognition that fits the observations described in Section 2.

The model distinguishes two types of neurons according to their different connections and hence different functions. I will call these neurons “image neurons” and “memory neurons”.

When I see an event, each quality of the event (shape, movement, color, distance, sound, smell...) is processed in parallel, each in hierarchical form. At the top level of these hierarchies are image neurons.

When I see the event, image neurons all over the cerebral cortex fire. In Figure 3 are shown three image neurons that fire in response to a particular external stimulus. The sub-set of image neurons that fires will be called an “image”.

The crucial question is this one: How can image neurons that fire all over the cerebral cortex synchronize their pulses?

To answer this question we introduce a memory neuron as shown in Figure

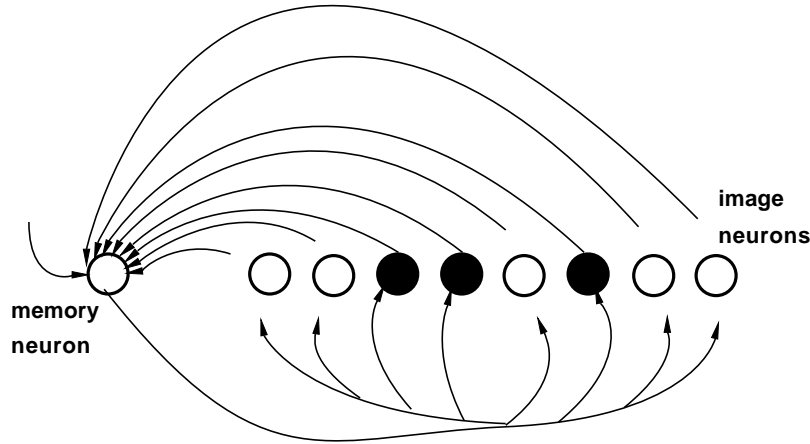


Figure 5: The same as Figure 4 but after the memory neuron has been programmed. Note that the synapses connecting the memory neuron dendrites and axon to image neurons that do **not** fire have been broken. The memory neuron and the black image neurons form a positive feedback loop. The black image neurons now fire in synchronism due to this feedback loop.

4. The unprogrammed memory neuron has its dendrites and its axon connected to many image neurons.

The memory neuron becomes programmed and encodes an image as follows. The memory neuron breaks the synapses of its dendrites and axon to the image neurons that are **not** firing. See Figure 5. This breaking of synapses is the storage of the image into the long-term memory. Each memory neuron can store one image. (It is important to mention that similar programming of neurons has been studied in kittens before the age of three months when the excess of synapses are broken to obtain registered binocular vision.[2]) From the experiments we speculate that the programming of a memory neuron takes of order  $\approx 1$  second.

The memory neuron serves three functions: recognition, short-term memory, and long-term memory as we now explain.

If I see the same event again, most of the same image neurons fire. This will cause the “memory neuron” to “recognize” the image and fire. This is how we recognize events. The firing of the memory neuron in turn **reinforces, synchronizes and completes** the firing of the image neurons involved in the perception. Thus a positive feedback loop is established. Even when the stimulus is removed the neurons keep firing in synchronism (at about 40 pulses per second[4]) due to the positive feedback loop of the memory neuron. The threshold of the memory neuron raises (or, equiva-

lently, the coupling weight of the synapses is reduced) so that after up to eight to twenty seconds the oscillation ceases. According to the model, this is the mechanism of short-term memory.

Examples of the brain completing images are the filling in of the blind spot, the coloring of periferal vision and the completion of a square.

If, for some reason, the memory neuron is excited, then the image neurons involved in the perception of the event fire in synchronism. The memory neuron “recognizes” this event, fires, and establishes a positive feedback loop. Self sustaining synchronized pulses occur for a few seconds. This is how the event is retrieved from the long-term memory and is “re-created” or “re-lived” in the short-term memory.

There is a hierarchy of memory neurons, so that if I see a dog coming towards me I first recognize a dog in general, and then I recognize the special dog Snoopy. The dog in general corresponds to a particular set of image neurons firing in synchronism. Snoopy corresponds to those same image neurons plus additional image neurons all firing in synchronism. A simple hierarchy is shown in Figure 6.

In Section 2 we mentioned that to transfer information from the short-term memory to the long-term memory it is necessary to classify it and relate it to other information already in the long-term memory. This classification and relation is the construction of the hierarchy of memory neurons such as the case shown in Figure 6. According to the model, this is the learning process.

We propose that there are memory neurons that recognize parts of images, *e.g.* a square, a face, the visual image of a letter, the sound of a word, the smell of a rose...

Consider Figure 3 again. I see an external event through my senses. As a result, image neurons all over my cerebral cortex fire. This firing is not in synchronism (yet). The qualities of the event (shape, movement, color, sound...) have not been related with each other. No memory neuron has recognized the image yet.

After a few hundred milliseconds memory neurons **recognize** the image, these memory neurons fire and synchronize the pulses of the image neurons all over the cerebral cortex. Positive feedback loops have been closed. The qualities of the event have been **related with each other**. The perception of the image no longer needs input from the senses since the positive feedback is **self-sustaining** for the next few seconds. Because the memory neurons form part of a hierarchy, the information of the image has been **related to other knowledge** in the long-term memory. The image may now become conscious.

If the feedback loops are prevented from oscillating we loose conscious-

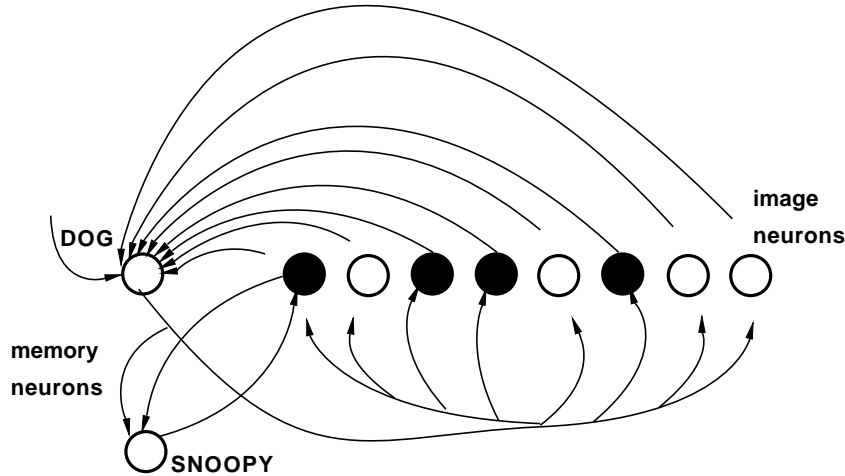


Figure 6: Two memory neurons are shown. The memory neuron labeled “DOG” recognizes a dog in general. The memory neuron labeled “SNOOPY” recognizes a special dog.

ness. General anesthesia “shuts off” consciousness by acting on the synapses. Likewise, the “center of sleep”, located near the hypothalamus, regulates the couplings at the synapses.

When a feedback loop oscillates we may become conscious of the corresponding image. The threshold of the memory neuron rises (or equivalently the coupling at the synapses is weekend) so that after a few seconds the oscillation is no longer self-sustaining. Then another memory neuron that codes a **related** image (and is therefore close to threshold) can begin oscillating, perhaps with the aid of input from the senses or noise. Thus **one image in conscience leads to a related image**. This is the “stream of consciousness”.

## 4 Estimates

The following are rough order-of-magnitude estimates. We humans have about  $\approx 10^{10}$  neurons. Our eyes have  $\approx 10^8$  rods and cones. The retina, which is part of the brain[5], processes the visual information so that “only”  $\approx 10^6$  axons connect the retina to the (rest of the) brain. Further processing will reduce this number. So a rough estimate of the number of image neurons (including all senses) is of order  $\approx 10^5$ . This number is of the same order as the maximum number of dendrites of a neuron. A very rough estimate of the number of memory neurons is obtained as follows: assume a memory neuron



is programed, *i.e.* an image is stored into long-term memory, every  $\approx 10$  seconds (the duration of short-term memory) for a lifetime. The corresponding number of memory neurons is of order  $\approx 10^8$ .

Let us now consider a bee. It has of order  $\approx 10^6$  neurons. The bee has eyes with a total of  $\approx 27000$  facets. After processing, we will need perhaps  $\approx 3000$  image neurons for all senses. If 10% of the bees neurons are memory neurons then they can store up to  $\approx 10^5$  images in long-term memory. So a worker bee that lives, say, six months, can store into memory about one image every minute or so. The bee will have some degree of consciousness.

## 5 Conclusions

The feedback loops shown in Figure 6 account for many observations on recognition, short-term memory, long-term memory and the learning process, and shed some light on consciousness. We propose that some implementation of those feed back loops is wide spread in the cerebral cortex.

We have not touched on the difficult questions: How does feeling (such as pain) arise from the firing of neurons? How do I become aware? Can a silicon neural network feel pain and become aware of itself? Does our attention wander randomly from one image to a related one, or do we have some control on our point of attention? How?

I hope the model serves as a point of departure for further experimental and theoretical research on the brain.

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